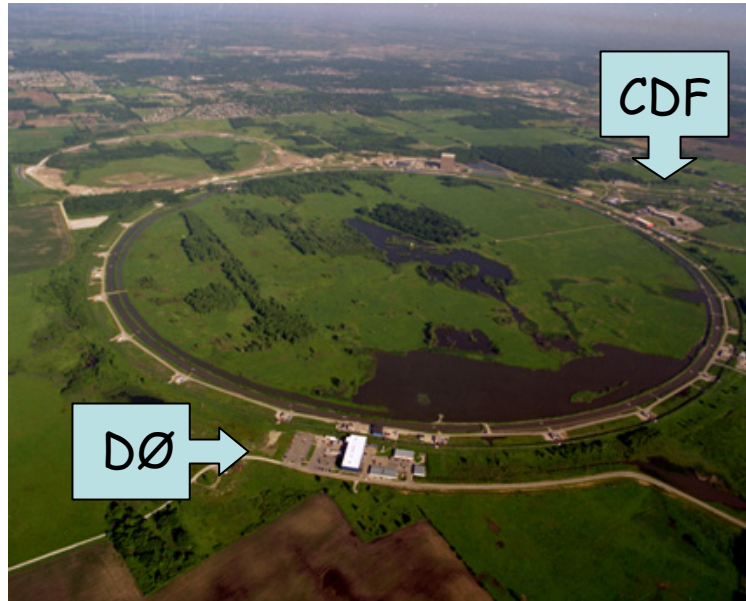


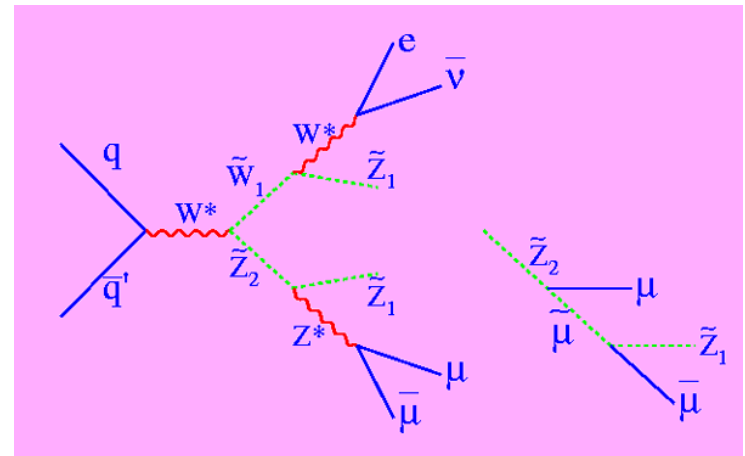
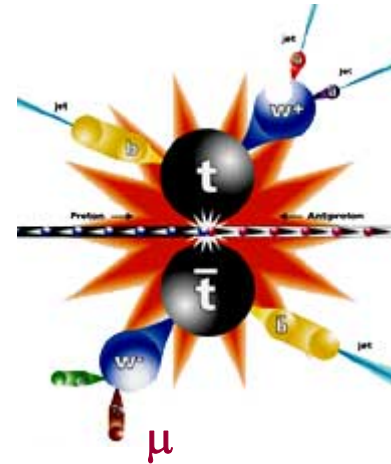
Muon Identification at the Tevatron



Jeff Temple
University of Arizona
for the DØ and CDF Collaborations

Why Muons?

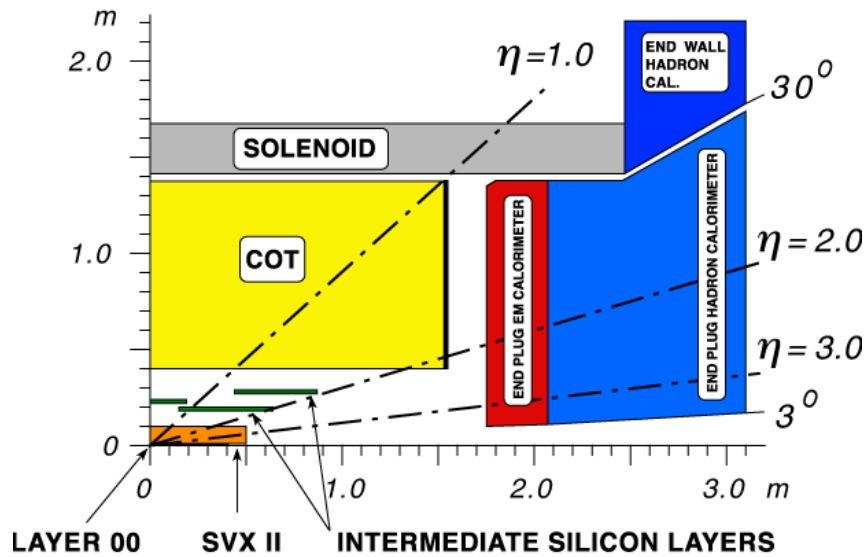
- Wide range of physics uses
 - Low- p_T : b physics
 - J/Ψ
 - b-jet, flavor tagging
 - High- p_T :
 - Electroweak - W & Z
 - Top - dilepton, muon + jets
 - new - Higgs, beyond SM
- "Simple" detection
 - Long lifetime
 - Minimal energy deposition
 - Little bremsstrahlung



Part 1: Detecting Muons

- Central tracker
 - Silicon
 - Fiber Tracker/ Drift Chamber
- Muon detectors
 - Scintillation Counters
 - Drift Chambers
- Magnets
- Shielding

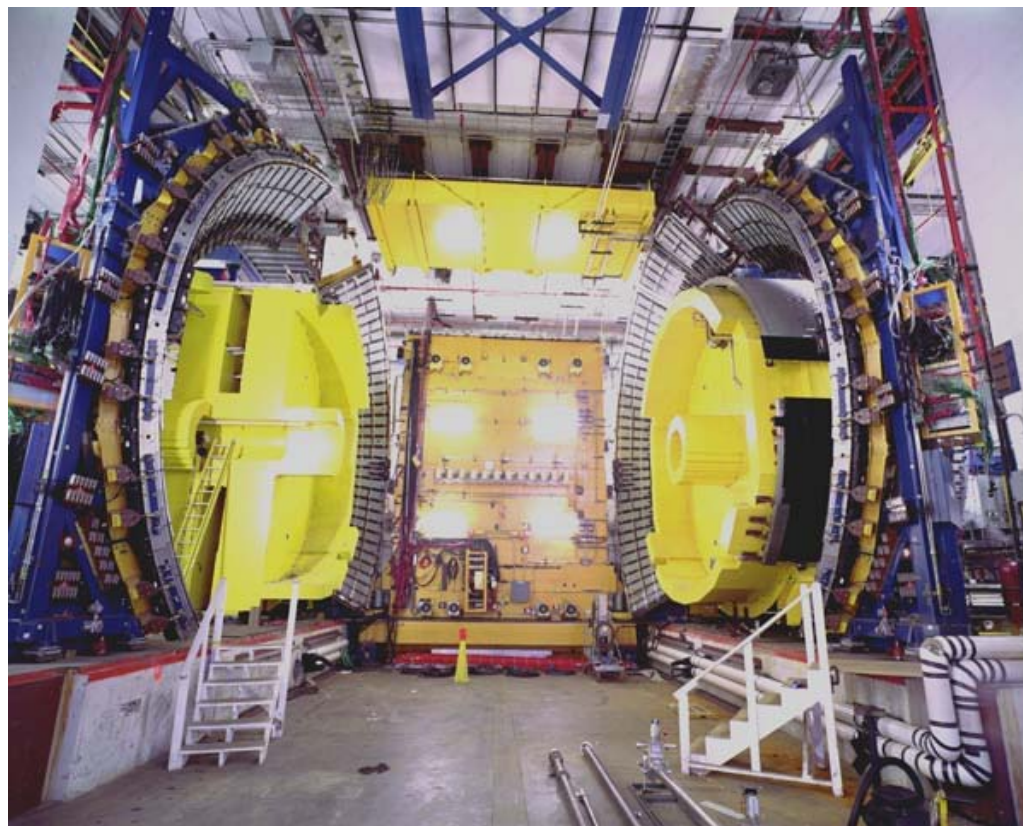
CDF Central Tracker



- SVX II:
 - 5 layers of double-sided silicon
 - $2.4 \text{ cm} < r < 10.7 \text{ cm}$
- ISL:
 - 3 layers of double-sided silicon
 - $20 \text{ cm} < r < 28 \text{ cm}$
- COT:
 - Open-cell drift chamber
 - 96 position measurements
 - $40 \text{ cm} < r < 137 \text{ cm}$
- 1.4 T solenoid

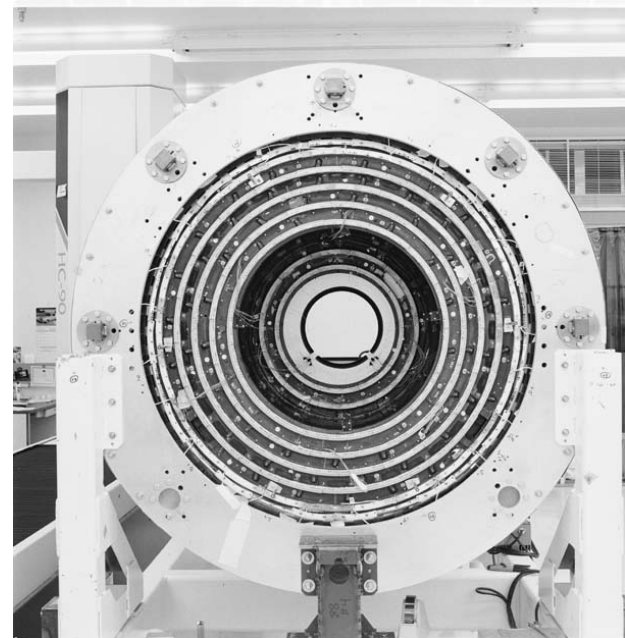
CDF Muon System

- Central Muons (CMUP/CMX):
 - $|\eta| < 0.6$ for CMUP
 - $0.6 < |\eta| < 1.0$ for CMX
 - Up to 8 planes of drift chambers
 - 1-2 layers of scintillators
- Forward muons (IMU):
 - $1.0 < |\eta| < 1.5$
 - 2 layers of scintillators
 - 4 planes of drift chambers
 - High backgrounds prevent triggering in this region
 - Counters in $1.5 < |\eta| < 2.0$ not currently used for reconstruction



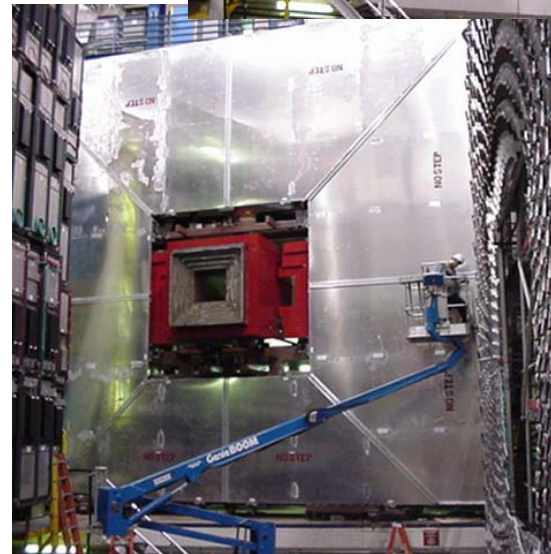
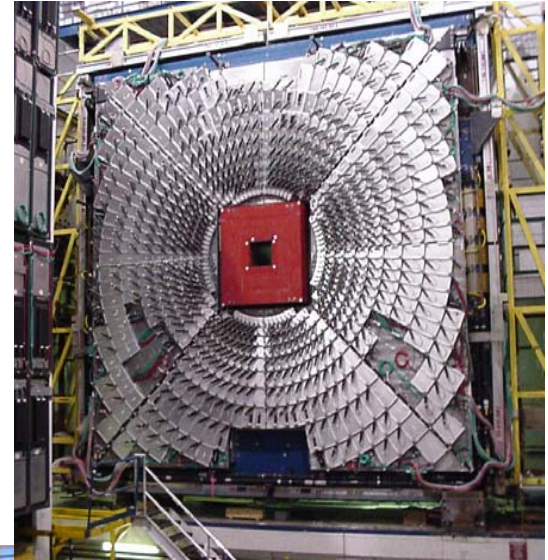
DØ Central Tracker

- SMT:
 - 6 barrels, 16 disks
 - 4 readout layers/barrel
 - Combination of single-, double-sided silicon
 - $|\eta| < 3$
- CFT:
 - 8 layer fiber tracker
 - 2 doublets/layer
 - $20 \text{ cm} < r < 52 \text{ cm}$
 - $|\eta| < 1.6$
- 2 T solenoid



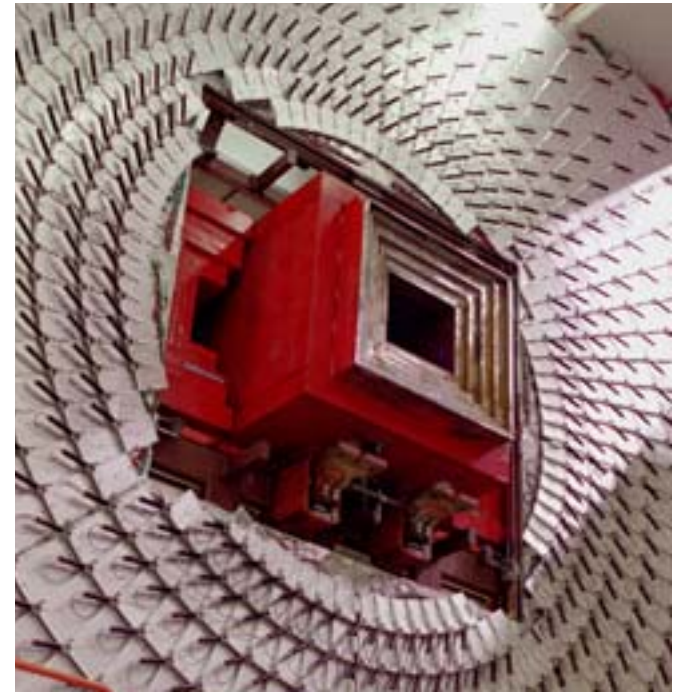
DØ Muon System

- Central ($|\eta| < 1$):
 - ≥ 2 layers of scintillators
 - 3 layer of drift tubes
 - 3-4 planes per layer of tubes
- Forward ($1 < |\eta| < 2$):
 - 3 layers of scintillators
 - 3 layers of drift chambers
- Toroid outside first layer of detectors



DØ Shielding

- Backgrounds from accelerator, small angle collisions
- Place shielding around beam pipe
 - 50 cm of steel - absorb hadrons and e/gamma
 - 12 cm of polyethylene - absorb neutrons
 - 5 cm of lead - absorb gamma rays



Reduces occupancy in muon counters by factor of ~100

Part 2: Triggering on Muons

- Three levels of muon triggering
- Each level adds additional event information
- Form single-muon, di-muon, muon+X triggers

CDF Muon Trigger

- **Level 1:**
 - COT track reconstruction via lookup tables
 - p_T cut on track (variable thresholds)
 - Match tracks to hits in muon system
 - Muon stub within 2.5° of track
- **Level 2:**
 - Tighter matching between track and stub
 - Additional p_T cut
- **Level 3:**
 - Full reconstruction
 - Match reconstructed track to muon hits

CDF Muon Trigger Rates

- CMUP

- Level 1:

- COT $p_T > 4 \text{ GeV}/c$
 - Muon hits $> 6 \text{ GeV}/c$

- Level 2:

- COT $p_T > 8 \text{ GeV}/c$

At $L = 100\text{E}30 \text{ cm}^{-2}\text{s}^{-1}$,
L1/L2 rates are:
132/12 Hz

- CMX

- Level 1:

- COT $p_T > 8 \text{ GeV}/c$
 - Muon hits $> 6 \text{ GeV}/c$

- Level 2:

- COT $p_T > 10 \text{ GeV}/c$

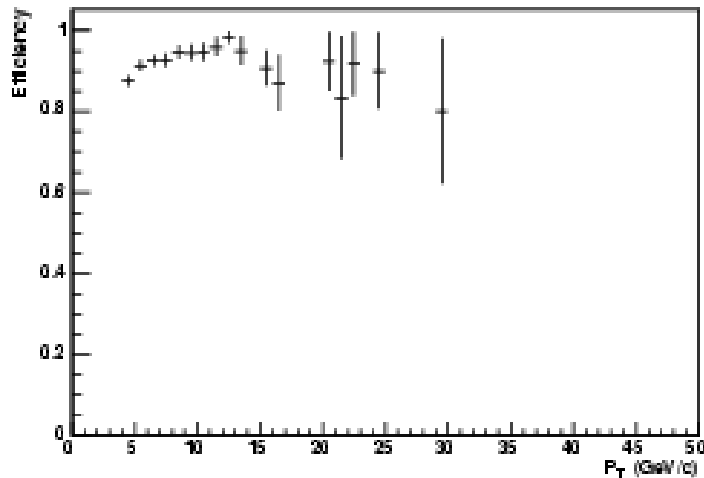
At $L = 100\text{E}30 \text{ cm}^{-2}\text{s}^{-1}$,
L1/L2 rates are:
12/9 Hz

DØ Muon Trigger

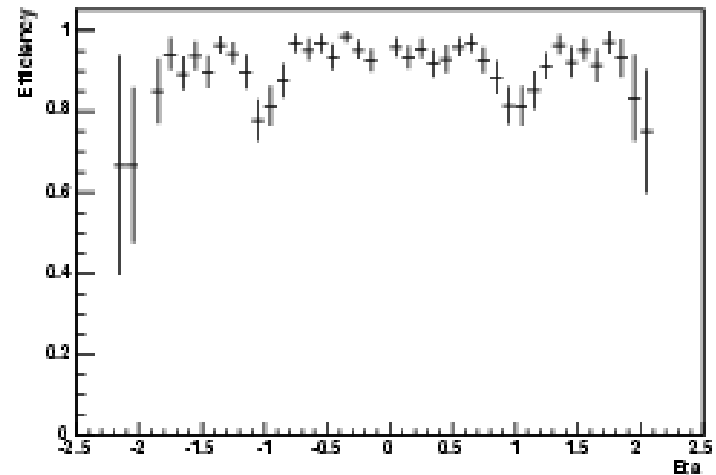
- **Level 1:**
 - Trigger on CFT tracks matched to muon hits
 - Triggers formed for 4 p_T thresholds
 - Can also form triggers independently of CFT
 - Single layer of scintillators and/or wires
 - Combination of layers inside and outside the toroid
- **Level 2:**
 - Uses wire times for more precise position information
- **Level 3:**
 - Match reconstructed central track to muon hits (χ^2 fit)

DØ L1 Muon Trigger Efficiency

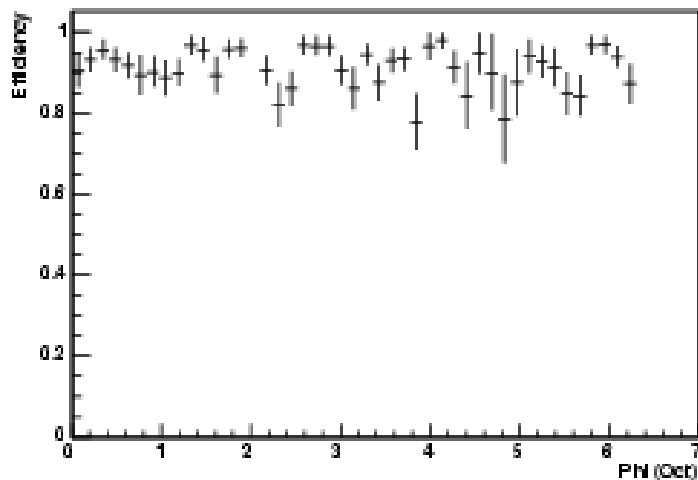
atlx eff pt



atlx eff eta

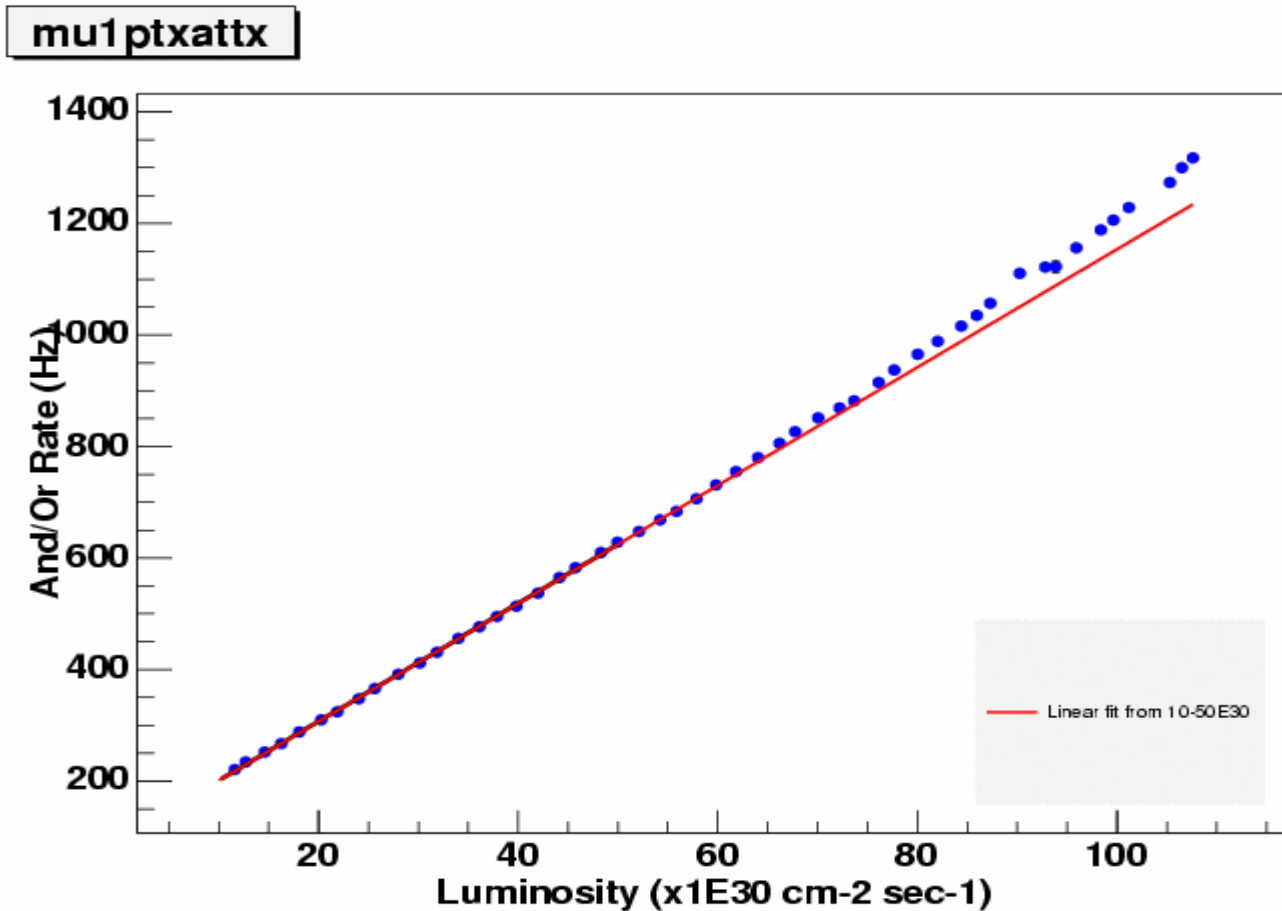


atlx eff phi



- Trigger requires 2 layers of scintillators and drift tubes
- Efficiency relative to muons with $p_T > 4$ GeV/c
- Efficiency $\sim 92\%$

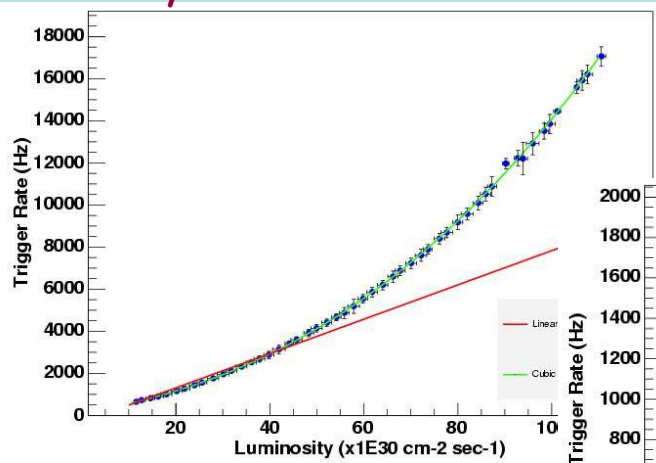
DØ L1 Trigger Rate vs. Luminosity



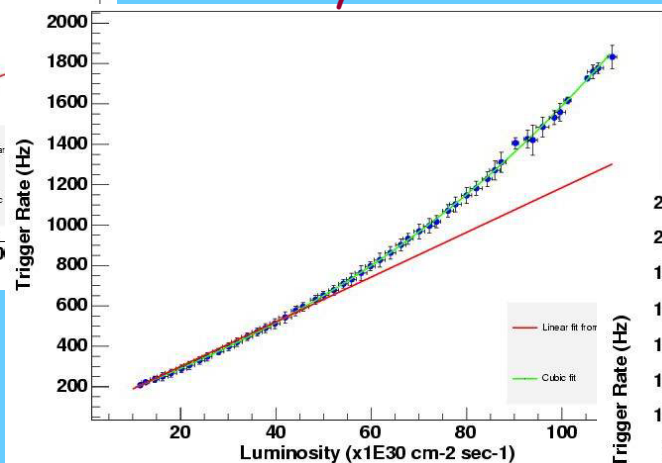
Require scintillator and wire hits inside and outside toroid
No track requirement

Level 1 ($|\eta| < 1.6$) Trigger

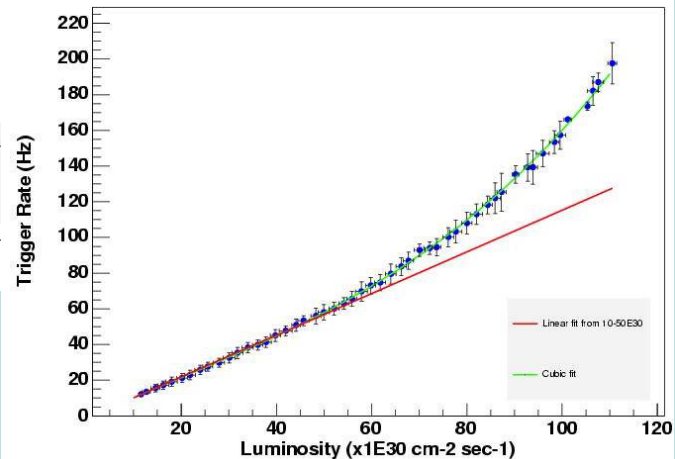
2 layers of scintillators...



...+ 1 layer of wires...



...+ 5 GeV/c CFT track



Adding detector components to the trigger
lowers the trigger rate by factor of nearly 100!

Part 3: Reconstructing Muons

- Project central track to muon system
- Look for match to muon hits
- Reconstruct muon from track with lowest χ^2
 - DØ also makes muon system-only χ^2
- Can also match to MIP signature in calorimeter

CDF Muon Reconstruction

- Categorize by region:
 - CMUP, CMX, IMU
- Muons with $p_T > 20 \text{ GeV}/c$ are "loose" or "tight"
 - Loose:
 - Track quality, isolation cuts
 - Small energy deposition in calorimeter
 - Tight:
 - Track projects to fiducial area of muon detectors
 - Cut on distance between muon stub and projected track position

DØ Muon Types

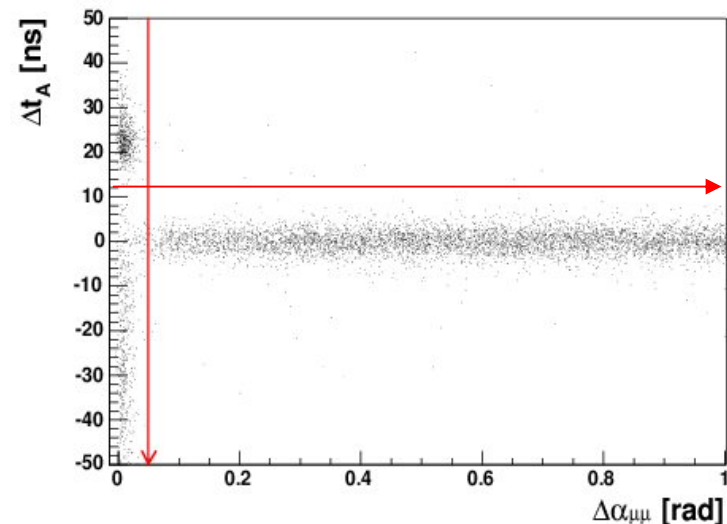
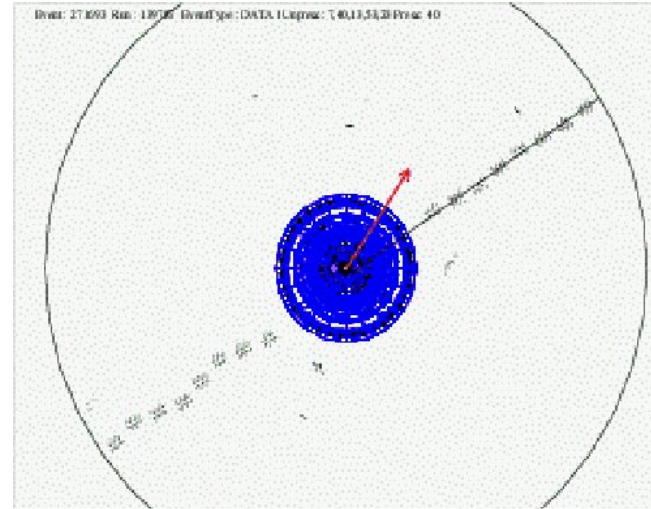
- Local muon: Formed from muon detectors only
 - “nseg” variable based on muon layers hit
 - $|nseg| = 1$: hits inside toroid (A layer)
 - $|nseg| = 2$: hits outside toroid (B/C layer)
 - $|nseg| = 3$: hits in A and B/C layers
 - $nseg < 0$: no central track match to local muon

DØ Muon Quality

- Tight Muons:
 - $|n_{seg}| = 3$ (Scintillator and wire hits inside and outside the toroid)
 - Converged local fit
- Medium Muons:
 - Same as tight, but with fewer wire hits required
 - No local fit required
- Loose Muons:
 - Scintillator hit + wire hits in the same layer

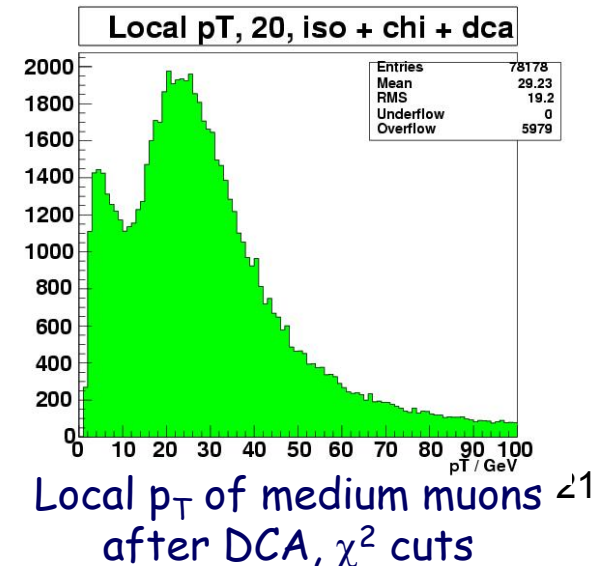
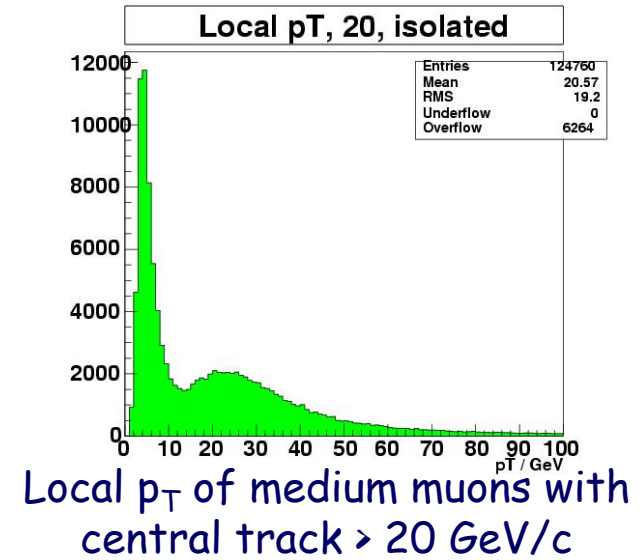
Rejecting Cosmics

- CDF identifies cosmics with central drift chamber
 - For each muon candidate, try to reconstruct its second leg
 - If found, test χ^2 for 1 or 2 particles
- DØ uses:
 - acolinearity of central tracks
 - Timing and timing difference between scintillators
 - DCA of muons



Rejecting Other Backgrounds

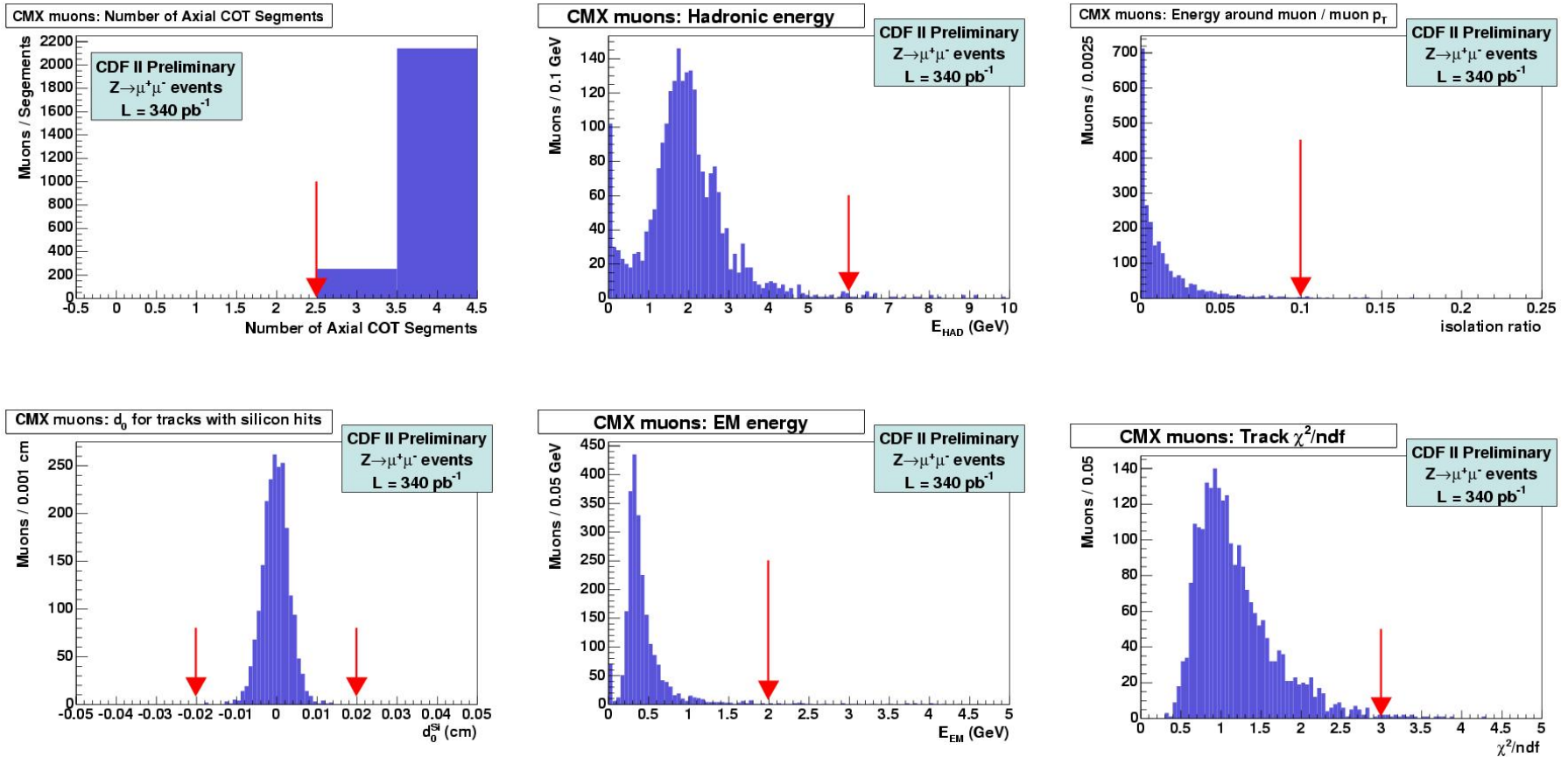
- In-flight decays (π/κ)
 - "Kinks" in central track
 - Apply DCA, χ^2 cuts
- Punch-through
 - Use increased quality criteria



CDF Muon ID Efficiency

- Use $Z \rightarrow \mu\mu$ events
 - Pass single muon trigger
 - Triggered muon tagged as "control" muon
 - $81 \text{ GeV}/c^2 < M_{\mu\mu} < 101 \text{ GeV}/c^2$
 - Test muon must pass:
 - Minimum COT hits
 - DCA between track, beam
 - Energy deposition in calorimeter
 - Isolation
 - χ^2 cut

CDF ID Efficiencies

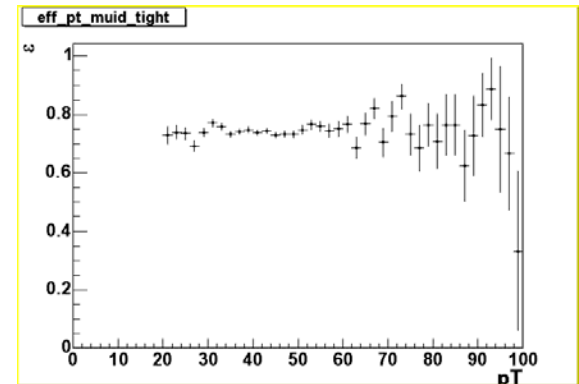
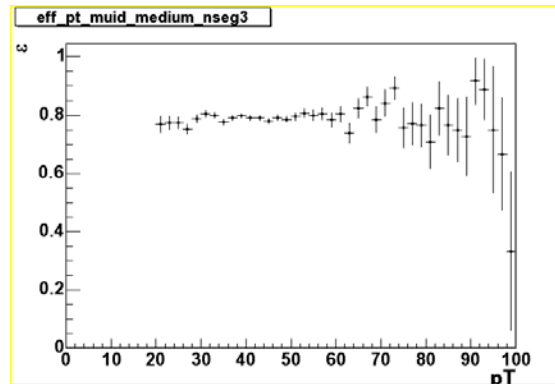
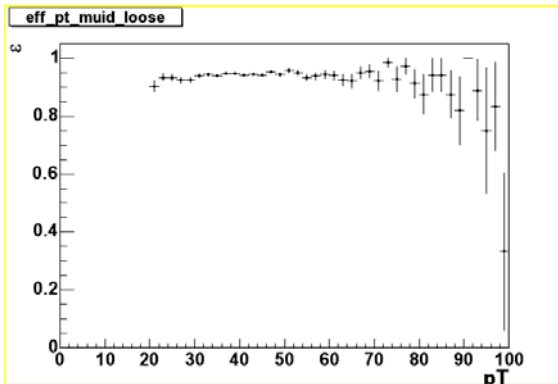
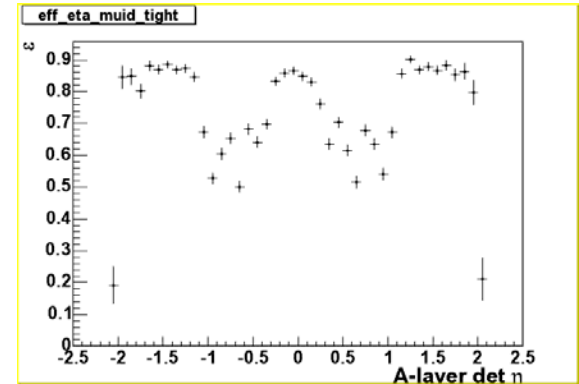
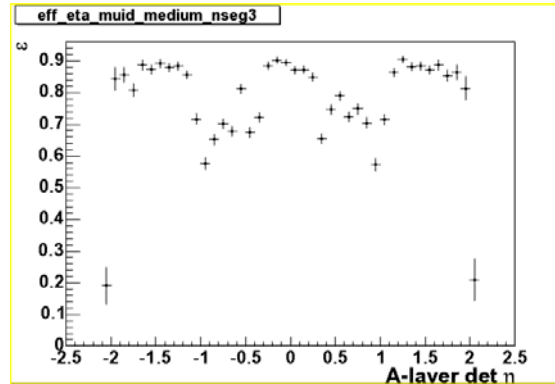
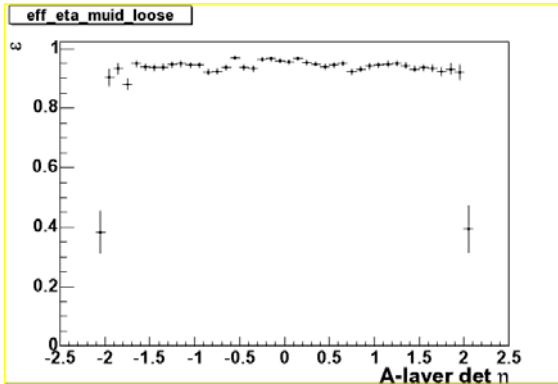


• CMUP/CMX Efficiency: 87%/93%

DØ Muon ID Efficiency

- Use $Z \rightarrow \mu\mu$ events
- Require 2 high- P_T CFT tracks
 - Control muon:
 - $P_T > 30 \text{ GeV}$
 - Matched to muon hits that fired muon trigger
 - Matched to Medium muon
 - A-layer scintillator hit time $< 10 \text{ ns}$
 - Test muon:
 - ≥ 8 CFT hits
 - $\chi^2 < 4$
 - Efficiency = probability to match test muon to muon ID object

DØ ID Efficiencies

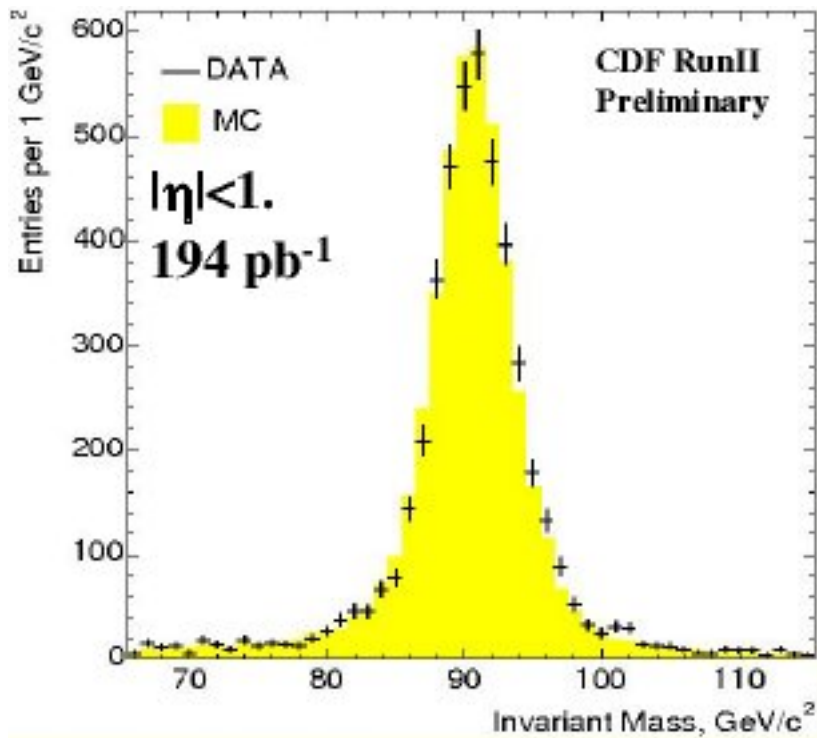


Loose: $94.6 \pm 0.1\%$

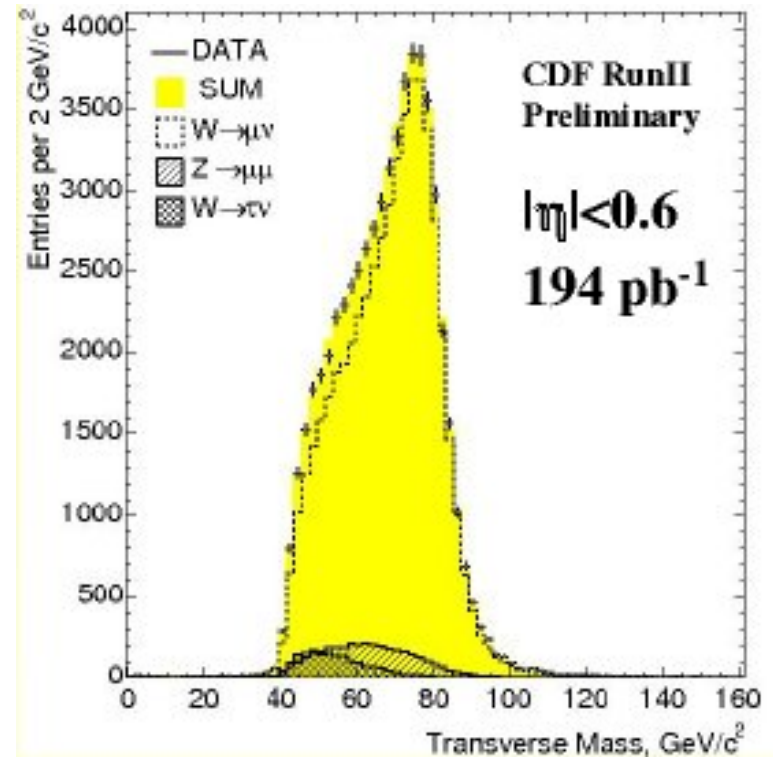
Medium, nseg=3:
 $82.1 \pm 0.2\%$

Tight: $78.2 \pm 0.2\%$ ₂₅

CDF Physics Results

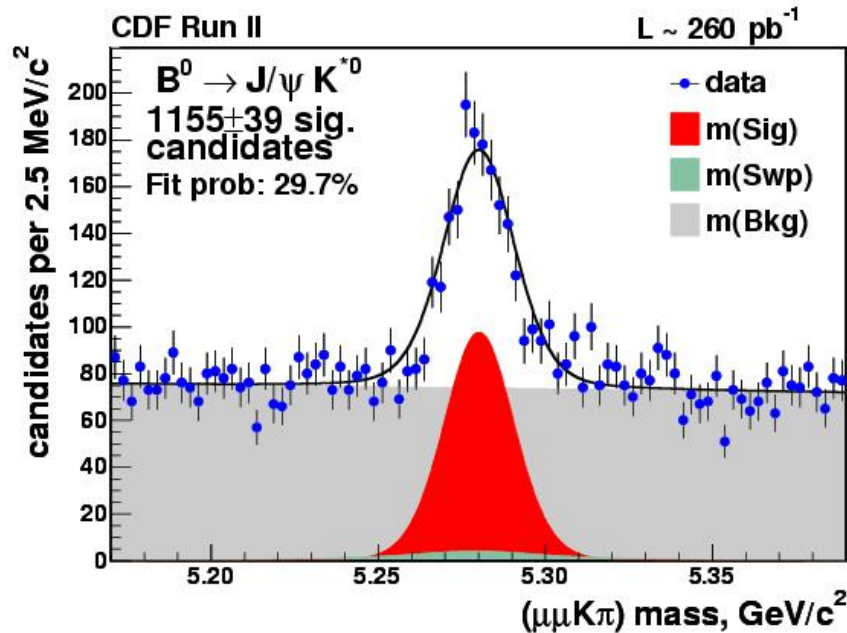


$Z \rightarrow \mu\mu$ invariant mass

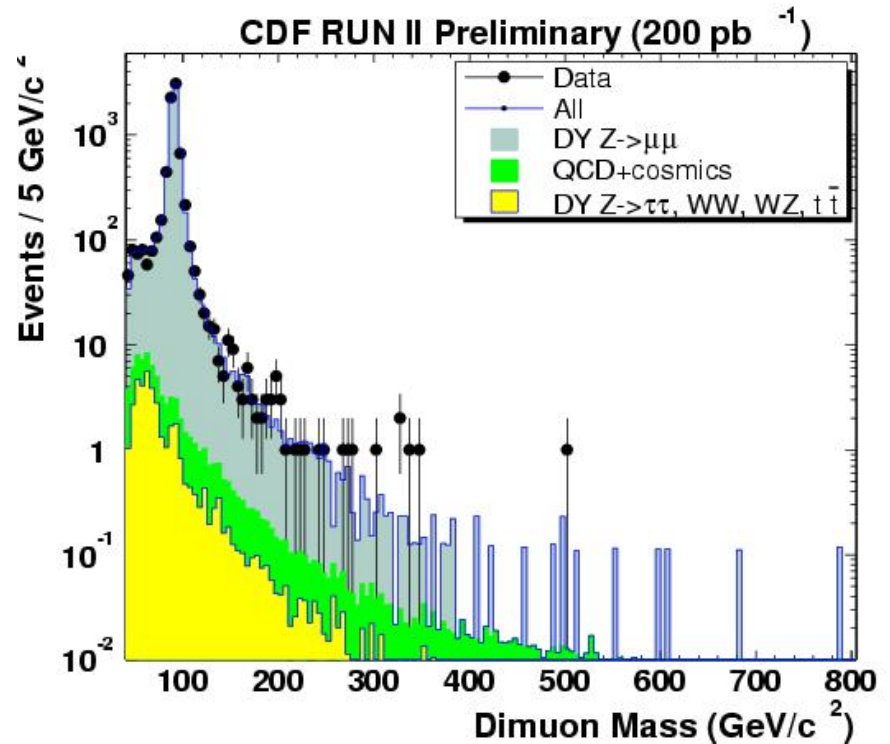


$W \rightarrow \mu\nu$ transverse mass

CDF Physics Results

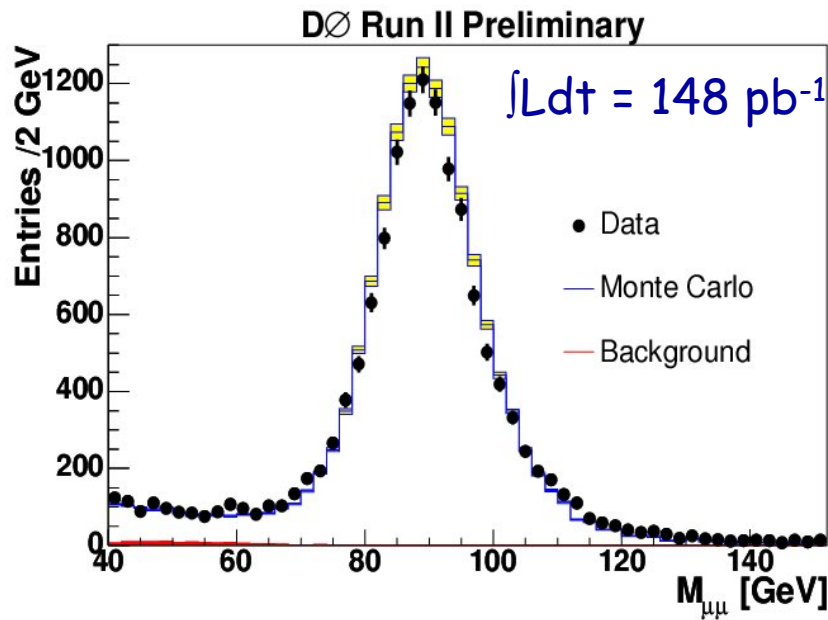


B^0 decay

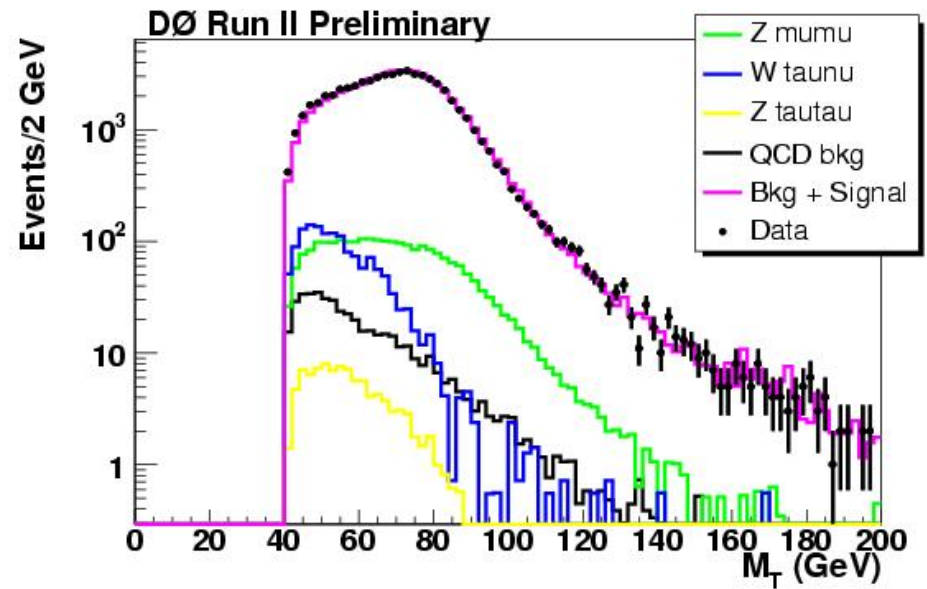


New Physics Search

DØ Physics Results



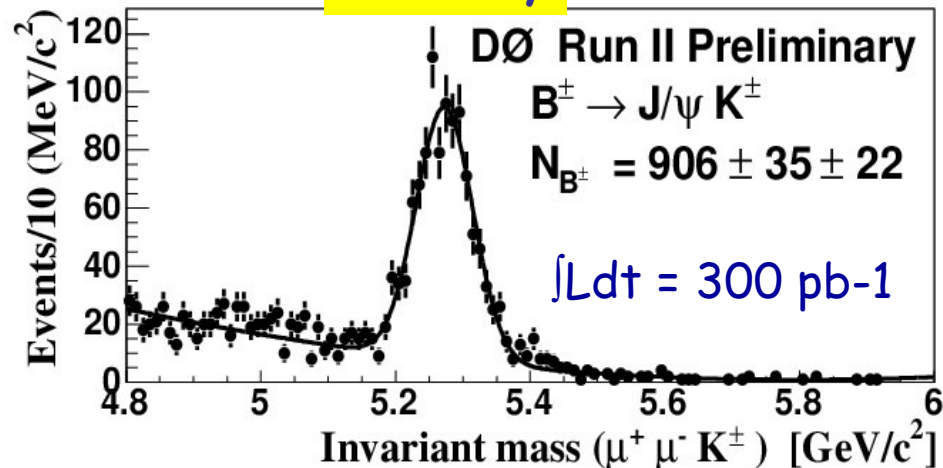
Z $\rightarrow \mu\mu$ invariant mass



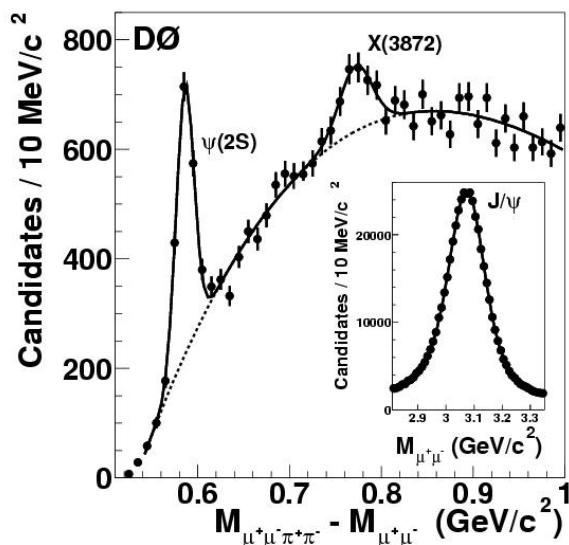
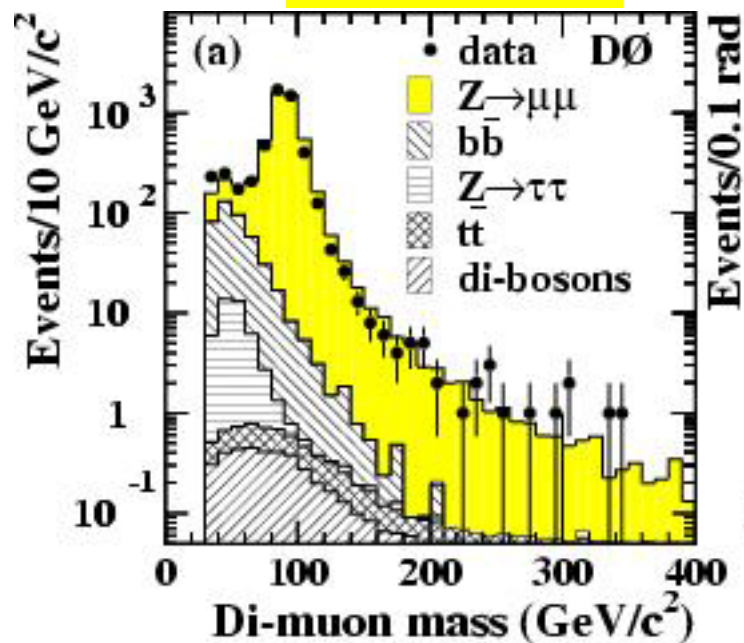
W $\rightarrow \mu\nu$ transverse mass

DØ Physics Results

B⁺ decay



Higgs search



X(3872)

Over half of DØ Run II publications have used reconstructed muons!

Lessons Learned

- Shielding is important!
- Difficulties in reconstructing across different regions

- **Flexibility is good!**

- Multiple detectors allow for tailor-made triggers
- Multiple reconstruction definitions provide flexibility for physics analyses



Backup Slides

DØ Muon Quality

- Tight
 - $|\text{nseg}| = 3$
 - ≥ 1 A-layer scintillator
 - ≥ 2 A-layer wire hits
 - ≥ 1 B/C scintillator
 - ≥ 3 B/C wire hits
 - Converged local fit ($\chi^2 > 0$)
- Medium
 - $|\text{nseg}| = 3$, fewer wire hits than Tight
 - $\text{nseg} = +1, +2$, at least 1 scintillator & 2 wire hits, bottom octants of detector
- Loose
 - ≥ 1 scintillator hit
 - ≥ 2 wire hits in same layer

Muon Type/Quality used depends on the physics analysis!!

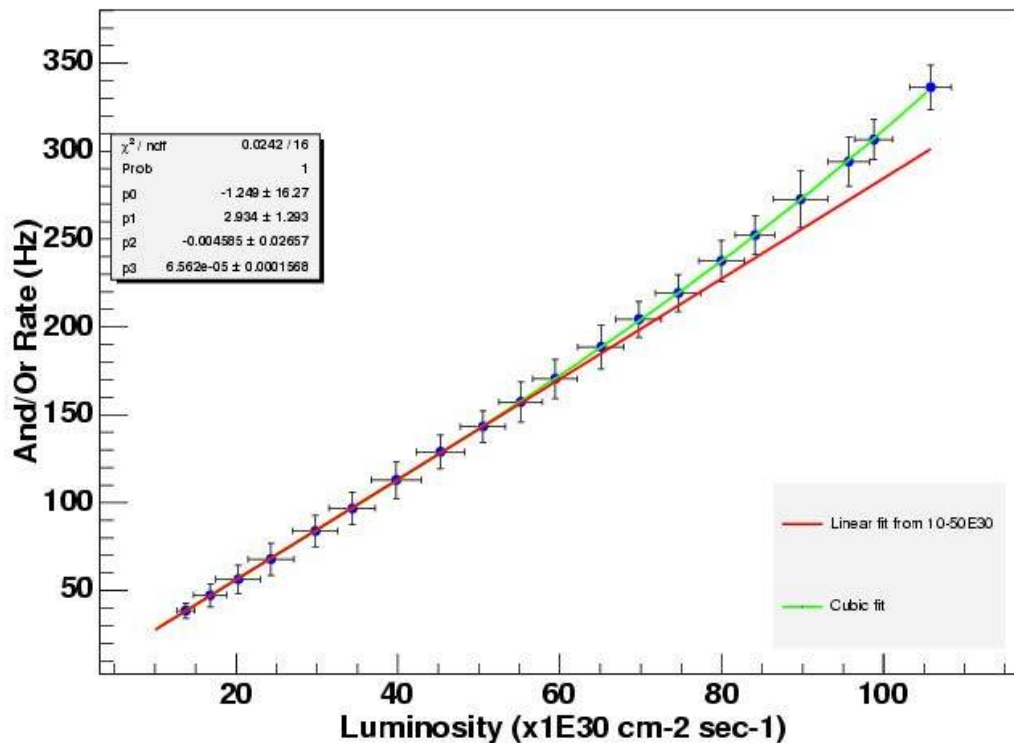
Sample CDF Trigger: Top Physics

- Level 1 requirement:
 - $P_T > 4 \text{ GeV}$ track matched to CMUP hit
 - $P_T > 8 \text{ GeV}$ track matched to CMX hit
- Level 2:
 - $P_T > 8 \text{ GeV}$ track
- Level 3:
 - $P_T > 18 \text{ GeV}$ track matched to muon hit
- Efficiency: $(88.7 \pm 0.7)\%$ for CMUP
 $(95.4 \pm 0.4)\%$ for CMX

mu1pt2wttx

mu1pt2wttx

Updated on Fri Jul 1 09:25:19 2005

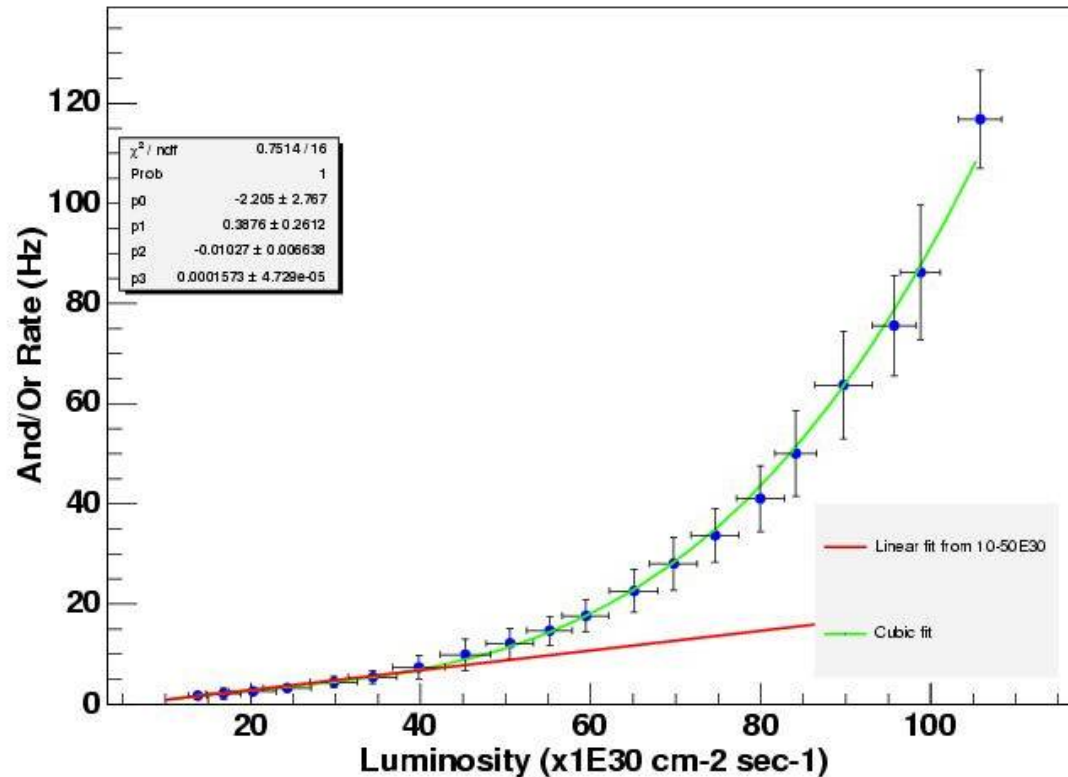


- 3 GeV/c central track, 2 layers of scint + wire

mu1pt4wtxx

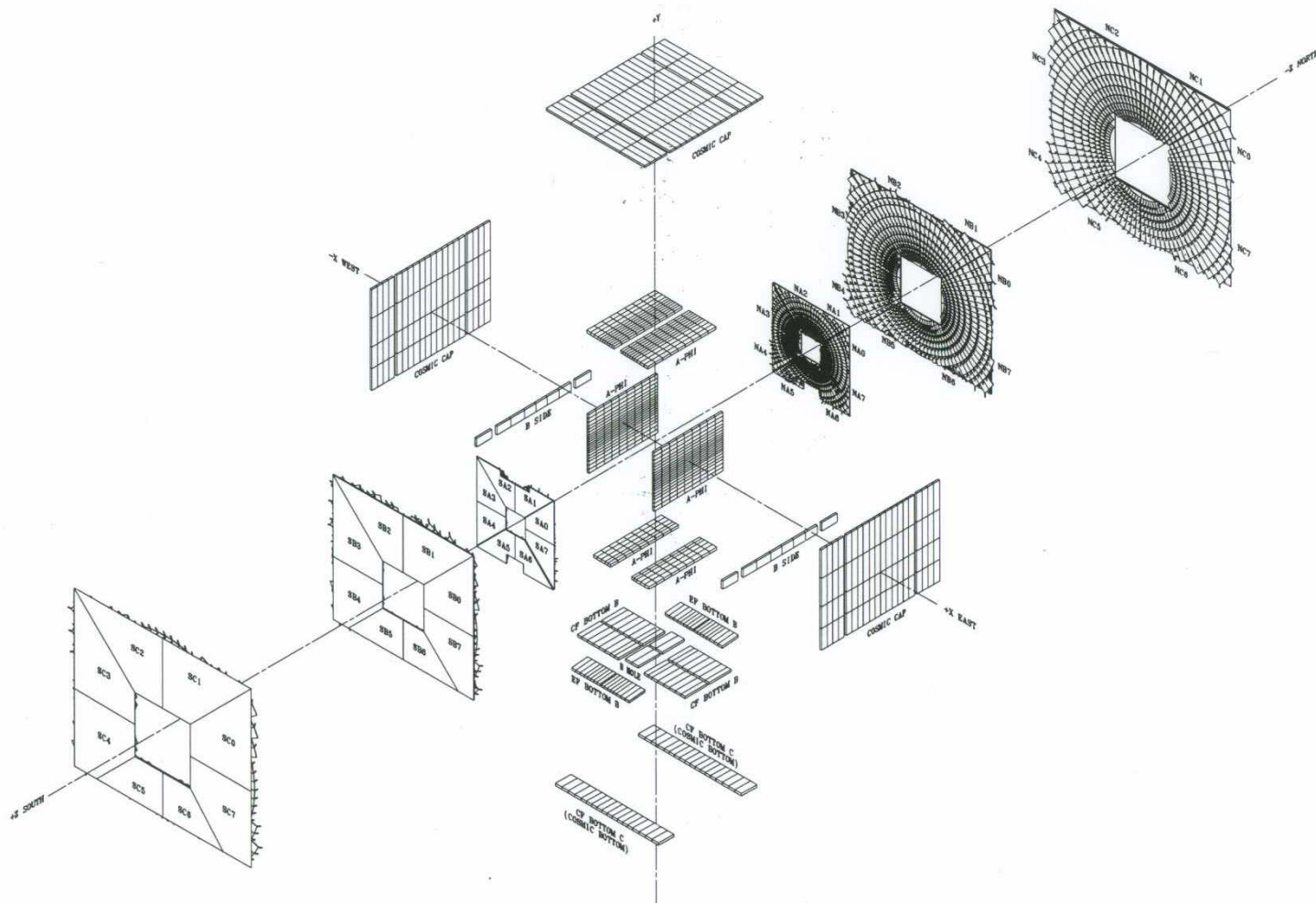
mu1pt4wtxx

Updated on Fri Jul 1 09:25:19 2005

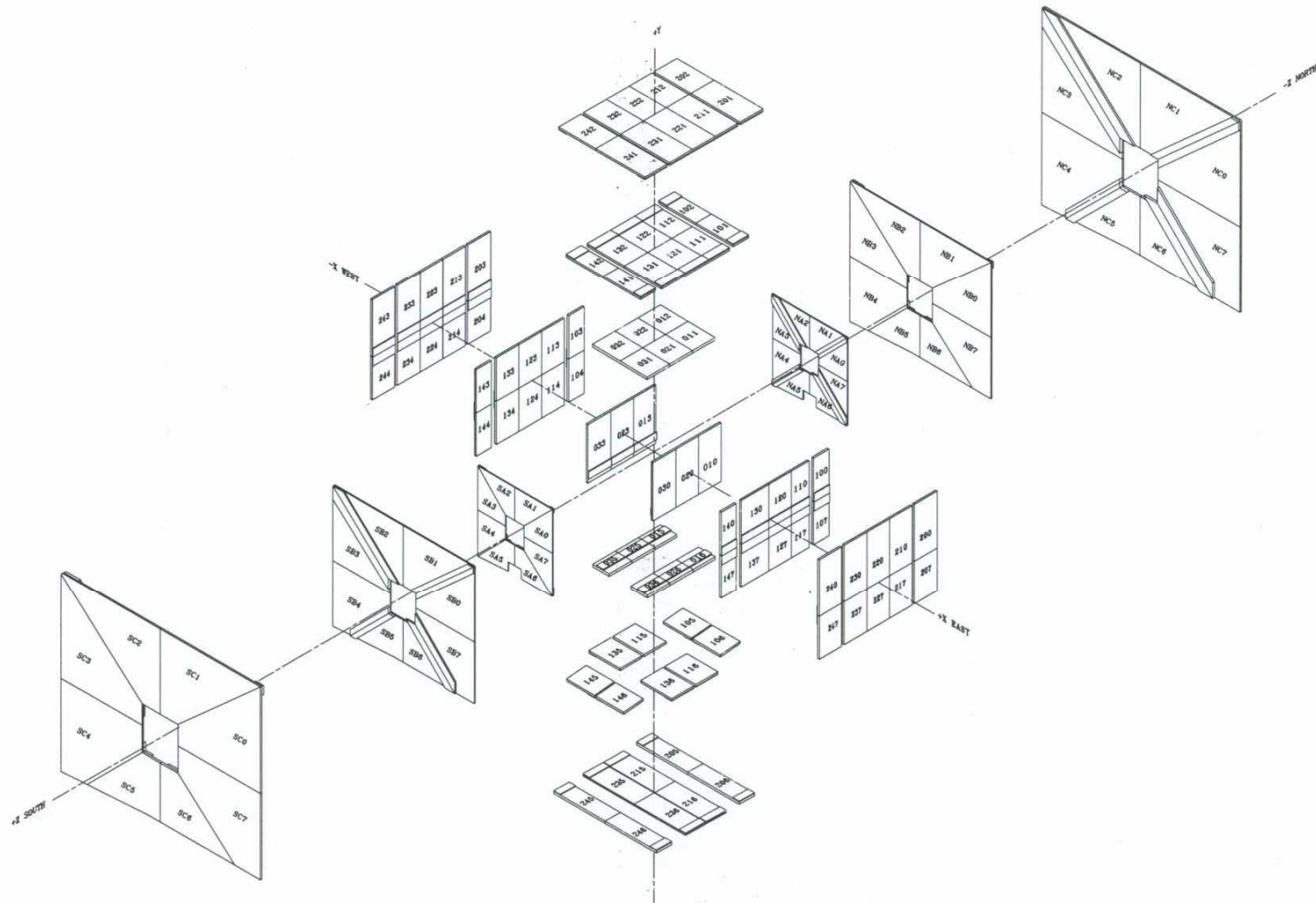


- 10 GeV/c central track, 2 layers of scint

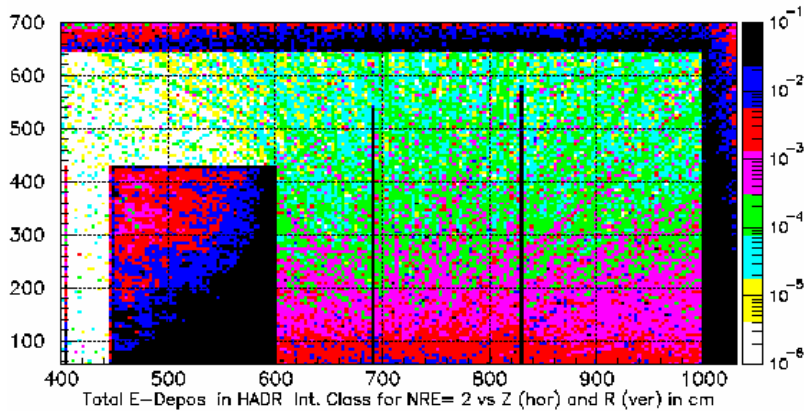
DØ Scintillator Counters



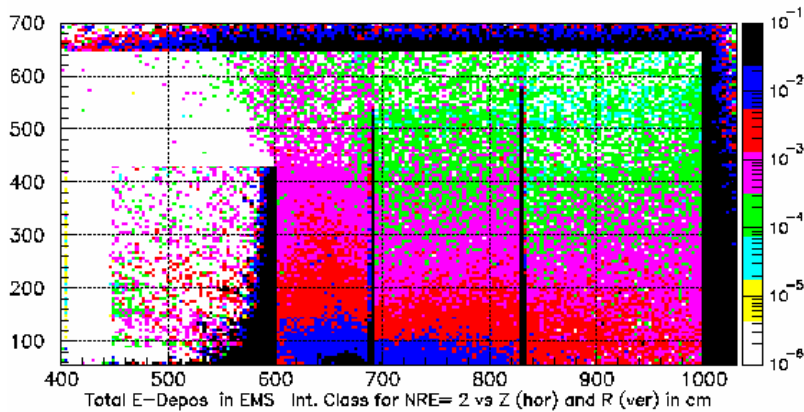
DO Wire Chambers



Effect of Shielding

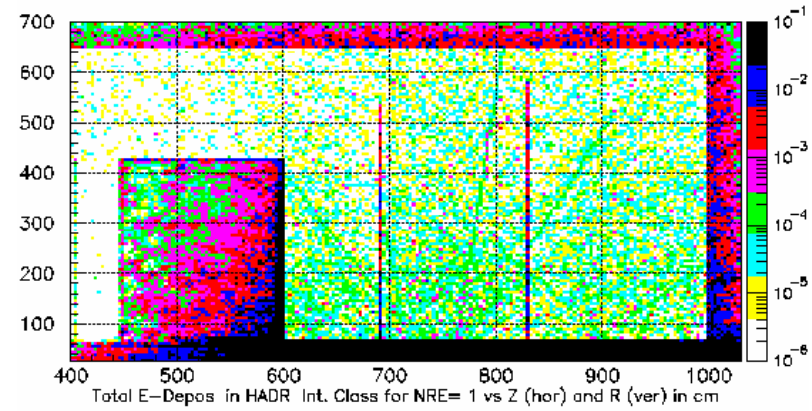


Hadron

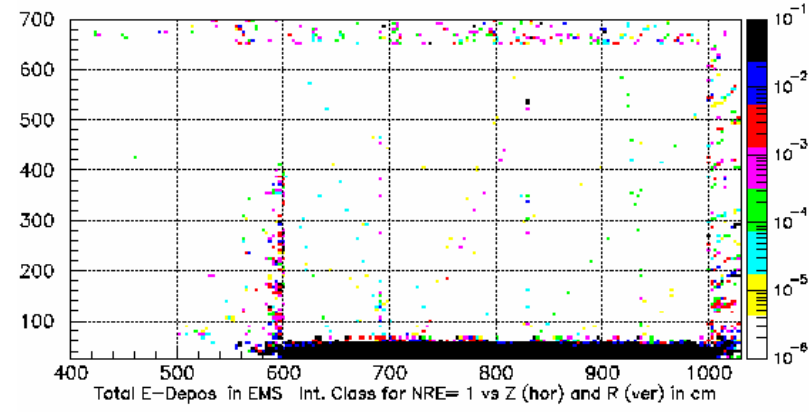


In units of 10^8 GeV/cm³ per sec, where the color indicates the power n

Without Shielding



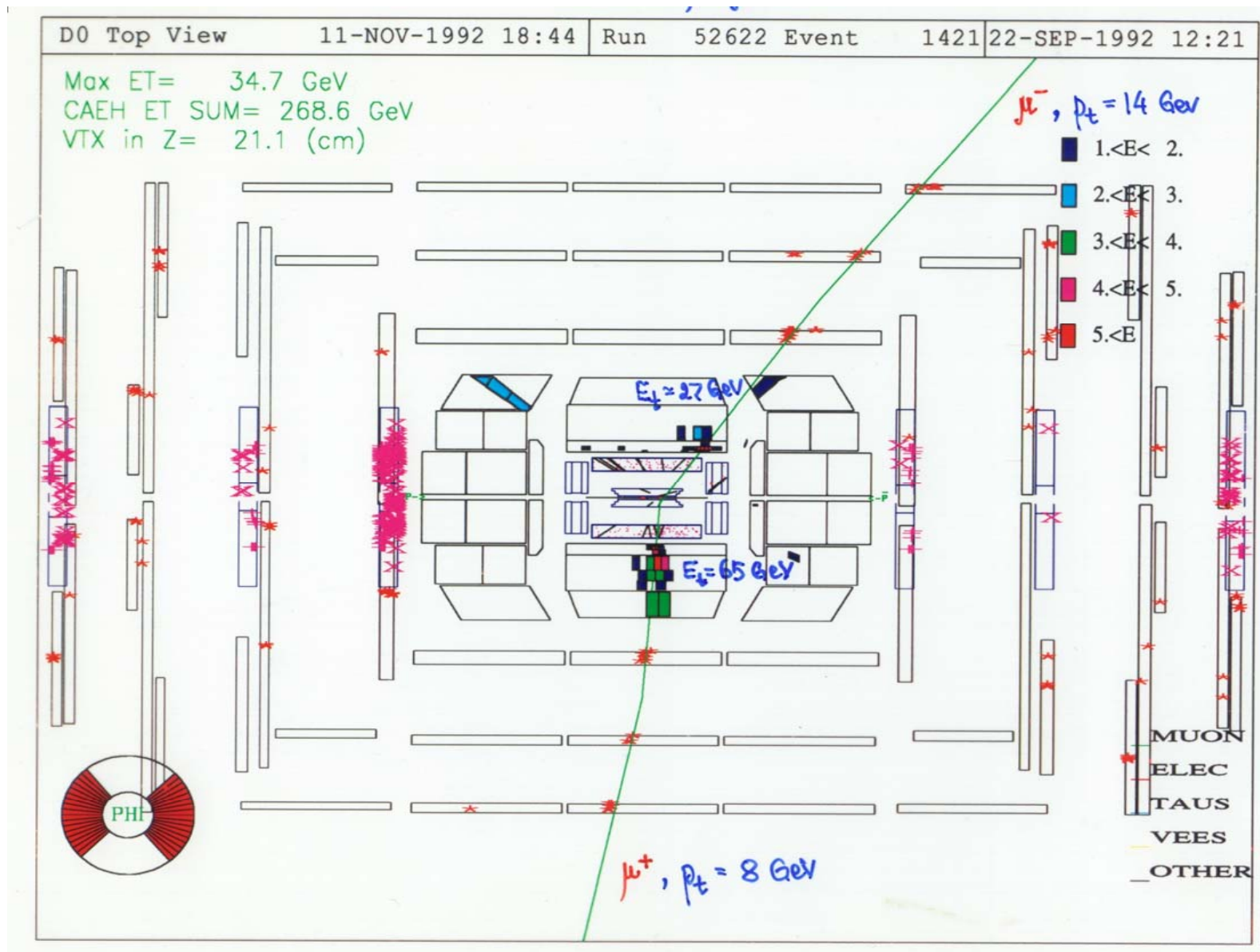
e/gamma



In units of 10^8 GeV/cm³ per sec, where the color indicates the power n

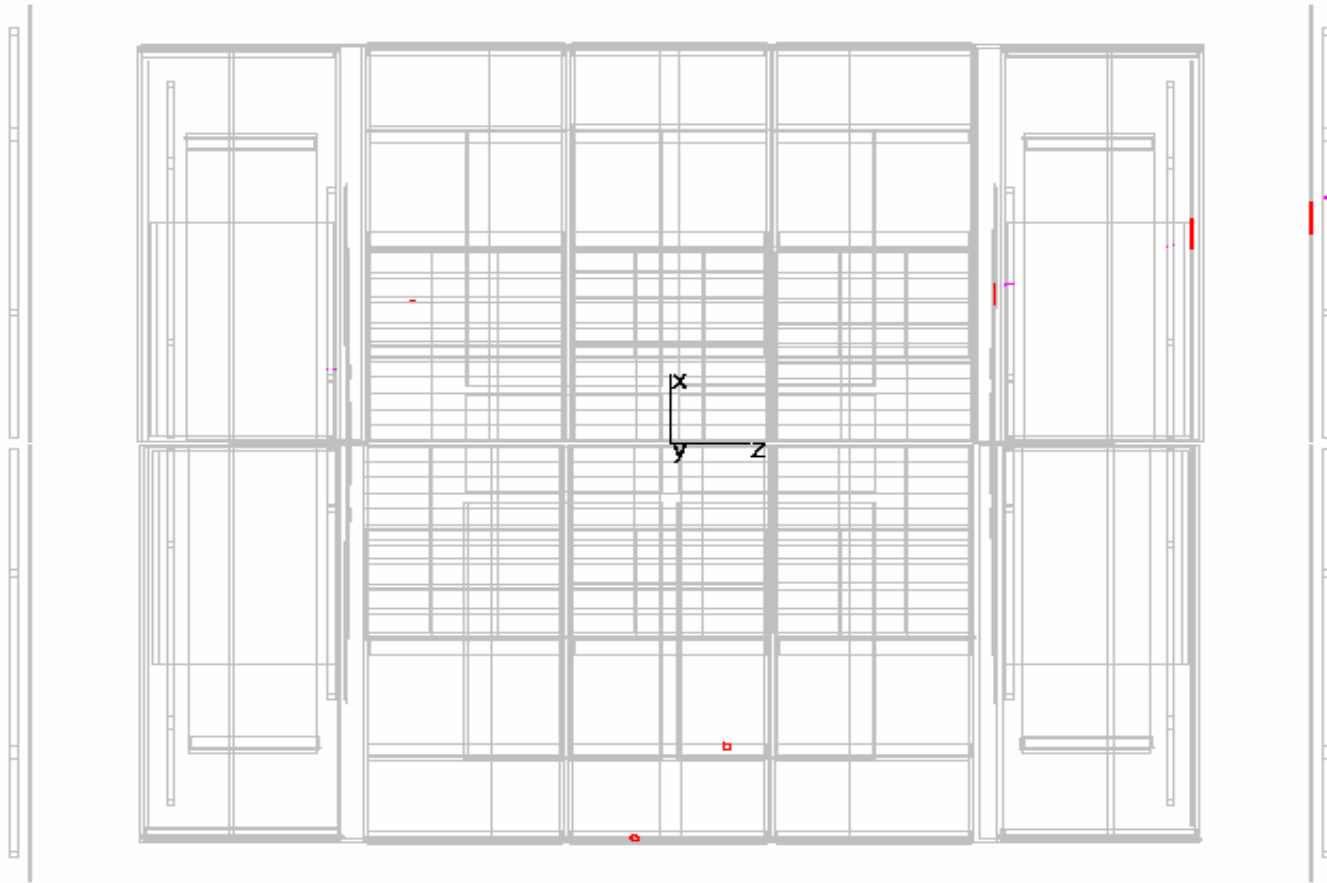
With Shielding

Run I "Typical" Event



Single Muon Run II Event

Run 148451 Event 5457036 Wed Apr 10 19:10:42 2002



Muon only detectors are shown